

The Challenges of Designing the Rocker-Bogie Suspension for the Mars Exploration Rover

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Abstract

Over the past decade, the rocker-bogie suspension design has become a proven mobility application known for its superior vehicle stability and obstacle-climbing capability [1,2]. Following several technology and research rover implementations, the system was successfully flown as part of Mars Pathfinder's Sojourner rover [3]. When the Mars Exploration Rover (MER) Project was first proposed, the use of a rocker-bogie suspension was the obvious choice due to its extensive heritage. The challenge posed by MER was to design a lightweight rocker-bogie suspension that would permit the mobility to stow within the limited space available and deploy into a configuration that the rover could then safely use to egress from the lander and explore the Martian surface. This paper will describe how the MER rocker-bogie suspension subsystem was able to meet these conflicting design requirements while highlighting the variety of deployment and latch mechanisms employed in the design.

Introduction

The primary role of the MER suspension subsystem is to provide the rover with a mobility system that has the kinematic range to permit the rover to safely traverse 20 cm obstacles and allow the wheel assemblies to rotate for rover "arc-turn" and "turn-in-place" maneuvers. In addition to these general traversability requirements, there were several requirements unique to the particular issues of the MER vehicle. Specifically, the suspension was required to 1.) Stow in an extremely small space and deploy the mobility into a stance that would provide the rover with 45 degree stability and 2.) Absorb a large percentage of the impact loads the rover would experience during lander egress and surface traverse.

The rocker-bogie suspension is a mechanism that, along with a differential, enables a six-wheeled vehicle to passively keep all six wheels in contact with a surface even when driving on severely uneven terrain (see Figure 1). There are two key advantages to this feature. The first advantage is that the wheels' pressure on the ground will be equilibrated. This is extremely important in soft terrain where excessive ground pressure can result in the vehicle sinking into the driving surface. The second advantage is that while climbing over hard, uneven terrain, all six wheels will nominally remain in contact with the surface and under load, helping to propel the vehicle over the terrain. MER takes advantage of this configuration by integrating each wheel with a drive actuator, maximizing the vehicle's motive force capability.

Another key feature of the suspension that has not been emphasized in previous technology and flight applications is the ability to absorb significant driving loads. In the past, rocker-bogie suspensions have been used on rovers where the loads generated during driving have been relatively low. Therefore, the suspension served primarily as a "rigid" kinematic link between the rover body and the wheels. However, the MER rover has the challenge of egressing from a lander poised on airbags and surface features, a maneuver that could require the vehicle to drop from a significant height above the surface. Instruments that had been stowed during the landing phase of the mission will be deployed during driving and were not designed to withstand large loads in their science-gathering configuration. A compelling design requirement was to therefore create a "soft" suspension to limit the accelerations experienced by the payload during driving. However, one of the more challenging design issues to address was how soft to make the suspension. A suspension that was too soft will result in large deflections where the rover body or its science appendages may contact Martian surface features in an uncontrolled manner. Therefore,

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the suspension had to be designed to give the rover a ride somewhere between a luxury vehicle and a truck. The suspension system stiffness target was one that would produce a translational impact load no greater than 6 G's and not let the rover body deflect below a 20 cm ground height. The resulting suspension structural members were fabricated from tapered, welded, titanium box beams tuned to meet these requirements. The design of these elements also provides exceptional bending and torsional capability while minimizing the volume and mass impact to the spacecraft.



Figure 1. Mars Exploration Rover with a Deployed Suspension

The last and most difficult design requirement was to create a suspension that would stow within the tetrahedral lander, unfold and latch into a deployed configuration, and provide the rover with the ground clearance and stability necessary to navigate the Martian surface. This task required significant coordination with other rover and lander subsystems in order to produce a deployment sequence free of static or dynamic interferences (see Figure 2 & 3).



Figure 2. Stowed MER Rocker-Bogie Suspension on Assembly Fixture

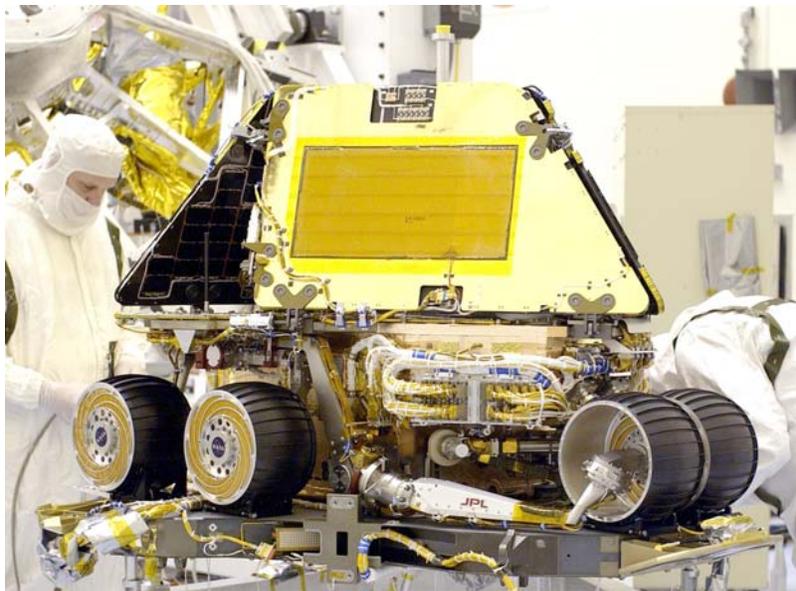


Figure 3. Stowed MER Rover on Lander Basepetal

Folding and Unfolding the MER Mobility

Determination of how the rocker-bogie suspension could be “broken” to enable it to stow within the allotted space was the first challenge faced in the design of the sub-system. As the name would suggest, the two primary components of this type of suspension are the rocker and bogie (see Figure 4). These two structural elements are connected via a free rotating pivot dubbed the Bogie Pivot. The right and left sets of rocker-bogie assemblies are connected to each other via the vehicle’s differential, a passive, motion-reversal joint that constrains the two sides of the mobility system to equal and opposite motion. Three unique break points were selected: the Rocker-Bridge Joint, a mid-span rocker folding joint; the Rocker Deployment Actuator (RDA) Joint, a motor driven deployment joint on the forward rocker arm, and a telescoping prismatic joint on the bogie member. Thus, a total of six joints must be reliably locked and latched into place during deployment to provide the rover with a safe and stable platform for driving.

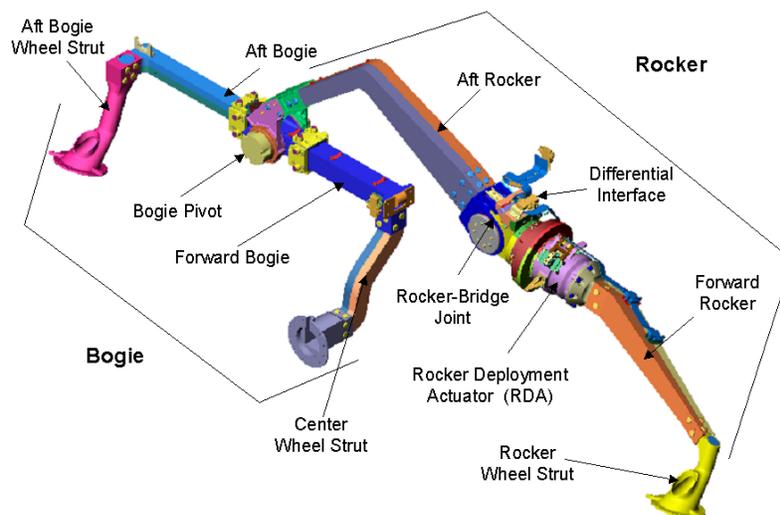
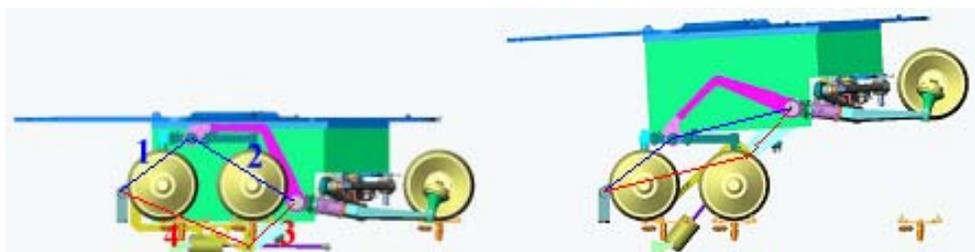


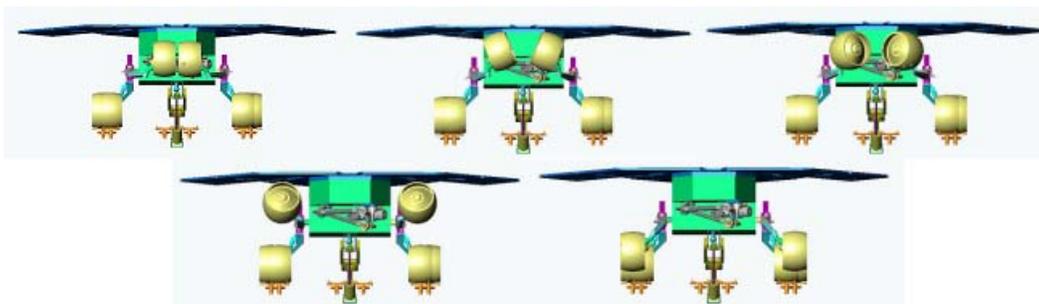
Figure 4. MER Suspension Nomenclature (Deployed Configuration)

Deployment of the rover takes place during the Standup and Deployment phase of the landed mission, after critical systems like the solar array and imaging mast have been deployed and the vehicle's health has been confirmed. The first step in deploying the mobility is to rotate and lock the Rocker-Bridge Joint into place. The MER mechanical design team had determined early on that a lander-based Rover Lift Mechanism, or RLM, would be needed to lift the rover from its stowed position. A rover-based RLM would have resulted in significant rover scar mass, as there would likely be a need for two actuators, one on each side of the rover, rather than one centralized device. As designed, the RLM utilizes portions of the suspension subsystem to create a four bar linkage that guides the rover body up into its ground clearing stance. By using the Bogie/Basepetal (Labeled 1 in Step 1) and the Aft Rocker (Labeled 2) as two links in a four bar linkage, the RLM needs only to provide the two remaining links and the extension force to raise the rover into its standing position [4].



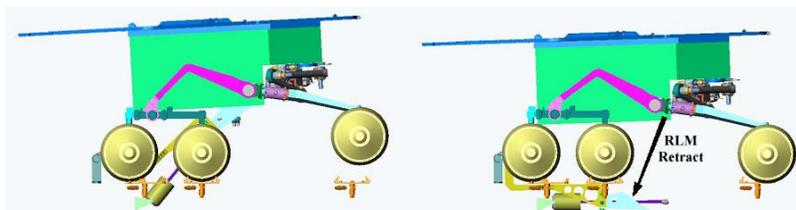
Step 1: Rover Lift

Once the body of the rover is lifted to its peak height, just beyond its nominal driving height, the second phase of rover stand-up begins. At the completion of Step 1, the forward rocker arm and the attached rocker wheel are still in their "up-side-down" stowed orientation. By activating the RDA on each rocker arm, the forward portion of the rockers is rotated 180 degrees into its full stance position. A mid-deploy-sequence steering motion was added to avoid interference of the wheels with the solar arrays. Once the RDA deployment is complete, the steering actuators are rotated to their forward driving orientation (see Step 2).



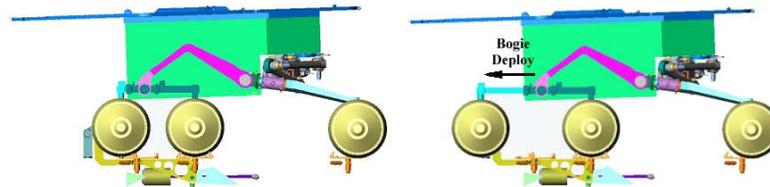
Step 2: Rocker Deployment (includes Steering Actuator rotation to clear Solar Arrays)

The third step in the stand-up sequence is the retraction of the RLM. Once the RDAs are deployed and latched into place, the rover is capable of supporting itself in its upright configuration. At this point in the deployment process, the rover is supporting itself on all six wheels (see Step 3).



Step 3: Rover Lift Mechanism Retraction

The fourth and final step in rover stand-up is the deployment of the suspension bogie member. A partnership was established with the wheel assembly subsystems to use the aft bogie wheels to pull the telescoping bogies out and latch them into their deployed position (see Step 4). By utilizing the wheel drives, the bogies can be deployed without the need to add two additional single use actuators. The only changes to the rover/lander system to enable this capability were a small redesign to the aft bogie wheel restraint and the addition of a cleated platform to ensure the aft wheel had the required traction to pull the aft bogie out of the forward bogie.



Step 4: Bogie Deploy

Material Selection

Titanium was used exclusively for the structural components of the suspension. This material was selected for several reasons. The high strength-to-weight ratio made it attractive for a mission where volume and mass was at a premium. In addition, the rover was mounted to a graphite/epoxy composite lander basepetal. Titanium's low CTE matched the lander's better than other potential suspension materials. Finally, the ability to weld titanium allowed the suspension structural components to be optimized for strength and flexibility. Eight of the ten suspension tube members were welded. The desire to increase the Ti-6AL-4V from the annealed to a solution treated and aged (STA) state was resisted. While the STA process would increase the strength of the titanium from 900 MPa (130 ksi) to 1100 MPa (160 ksi), the weld seams would remain in the annealed condition, creating an obvious and unacceptable weak link that could only be mitigated if the STA process was performed after welded. The possibility that the weld members would distort significantly during the STA process due to their thin walled construction was deemed too risky to accept. Therefore, all the suspension tube members were kept in their annealed condition.

Structural Member Fabrication

The desire to create a suspension that efficiently absorbs energy leads to structural members that are thin walled box beams. A box beam design is a mass efficient geometry for components subjected to both bending and torsional loads. The beams are also tapered wherever possible to increase mass savings. Based on these desired design features, the fabrication method selected to create the members was electron beam welding. The use of welding in the space industry is usually reserved only for propulsion tanks and tubing due to fears of poor workmanship and difficulty of inspection. Propulsion subsystems can be pressure tested to verify weld integrity. Spacecraft structure, on the other hand, does not typically lend itself to such proof loading methods. Because of these potential complexities, other alternative avenues of manufacturing were investigated, the most promising of which was investment casting. However, the small number of parts made this option prohibitively expensive per piece, so welding was ultimately chosen as the fabrication method.

The basic construction of each weldment is the joining of two C-channels. A less expensive option of welding a plate on an open box places the weld seam in the corner of the box beam was initially investigated. This location is undesirable due to the fact that the corner of the beam is the location of maximum stress in torsional load cases (see Figure 5), and therefore necessitates the more complicated C-channel approach. The typical wall thickness of 1 mm increases to 1.5 mm along the weld seam for extra strength. This design process also enables additional features to be machined into the welded members. The aft bogie member has a recess machined into it for the bogie latch pawl to reside. The "knees" in the aft rocker and center wheel struts are thickened up to accommodate the localized increase in stress.

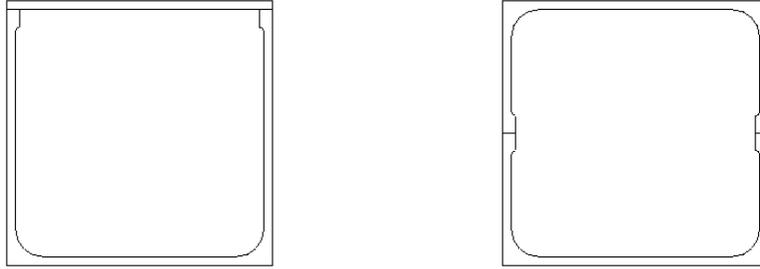


Figure 5. Open Box/Plate & C-Channel Options

After the selection of the fabrication process, a set of torsion tests were performed on 30 mm by 30 mm articles that were representative of the base of the forward rocker weldment. The torsional load in that location was 421 N-m (3725 in-lb). The test results indicated that the failures began near the corner of the weldment rather than the weld seam. Test results also demonstrated the box beam's tendency to yield rather than break at loads far in excess of its design capacity. This type of failure meant a driving impact case greater than the design load would result in "graceful degradation", allowing the surface mission to continue instead of causing a catastrophic system failure.

Detailed Description of Suspension Mechanisms

Rocker Bridge Joint and Latch Design

The rocker-bridge joint is essentially a yoke and clevis design. Each single-use joint pivots on two (2) 52 mm diameter Torlon 7130 thrust/radial bushings. Braycote 601EF grease is applied to the bushings as an added measure of friction reduction. Once deployed, the rocker-bridge joint needs to withstand a maximum 714 N-m (6325 in-lb) bending load generated when the center wheel falls into a 20-cm hole. The joint also simultaneously sees a 506 N-m (4475 in-lb) torsion load created by the 12 cm lateral offset between the rocker-bridge joint and the mobility wheels (see Figure 6).

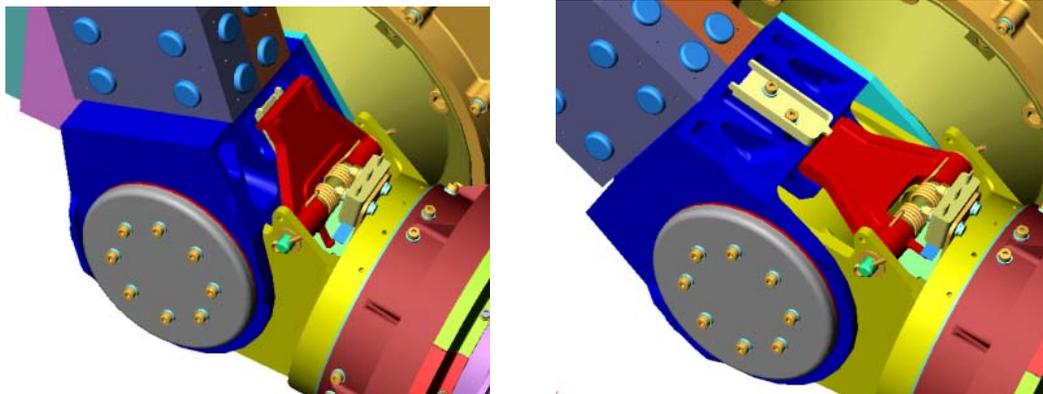


Figure 6. Rocker-Bridge Joint in Stowed & Deployed States

The rocker-bridge latch consists of a pawl that falls into place once the aft rocker has rotated 39 degrees from its stowed position. A small appendage on the forward side of the pawl was included in the pawl design to engage the microswitch lever arm to indicate the joint has successfully been locked. An intermediate step was also added to the latch design in order to isolate the latch from RLM stall loads. The intermediate latch position allowed the latch pawl to travel past its final position, causing the RLM to stall against its own internal hard stop rather than against the latch, which avoids unnecessary latch and suspension loading. Instead, once the RLM has stalled at the top of lift, it then lowers the rover and the latch pawl falls into its final latched position (see Figure 7).

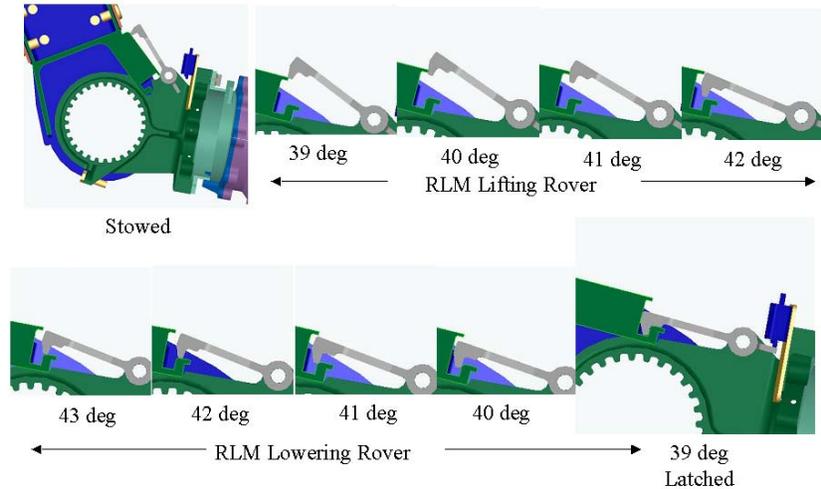


Figure 7. Rocker-Bridge Latch Pawl Action during the RLM Lift and Lower

Rocker Deployment Actuator and Latch Design

The triangular shape of the lander basepetal was a strong motivator to stow the front wheels directly in front of the rover. Following this motivation, a joint called the rocker deployment actuator (RDA) was added to the suspension to permit the front wheels to be stowed directly in front of the rover. During deployment, the RDA deploys the front wheels into a position that maintains the necessary rover pitch and roll stability. Once deployed, the RDA is required to withstand 390 N-m (3450 in-lb) bending and 421 N-m (3725 in-lb) torsional loads. The RDA is a 100-mm long, 80-mm diameter cylindrical body. A Maxon REO20 DC brushed motor with integral 5 stage planetary gearhead is employed to create the RDA's 20 N-m (175 in-lb) torque capability. The maximum predicted flight deployment load is 2.8 N-m (25 in-lb), giving the actuator considerable margin over its required task. Two pairs of 57.2-mm (2.25 in) diameter MPB angular contact bearings are utilized as the RDA's rolling elements (see Figure 8). The latch design chosen was based on a latch used on the Magellan spacecraft to latch the spacecraft's solar panels in place. The RDA latch can best be described as a variation on the common door latch. The two primary components of a door latch are the spring-loaded pawl in the door and a fixed strikeplate attached to the doorframe. The RDA latch inverts the dynamic and static roles in this latch design by fixing a pawl on the stator housing and allowing the rotor mounted strikeplate to pivot. In an effort to minimize the latch load, the diameter of the RDA was made as large as possible, the primary restrictions being the RDA's proximity to the lander side and base petals, rover body, and science hardware.

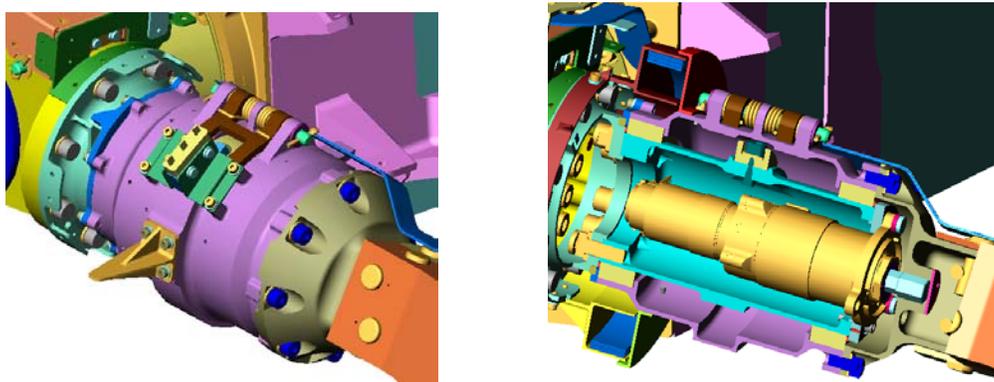


Figure 8. Rocker Deployment Actuator

Bogie Deployment and Latch Design

The original design of the MER suspension was one with a bogie of fixed length. As the MER rover design began to mature, its center of gravity began to rise. The flight system held a firm requirement that the rover would be stable to at least 45 degrees in vehicle pitch and roll. The increase in rover c.g. meant that the driving position of the aft bogie wheel needed to move backwards in order to meet the 45 degree stability requirement. Due to the volume constraints placed on the mobility in the stowed configuration, the bogie design needed to be modified to deploy, allowing an increase of the bogie length by an additional 17 cm.

The decision on how to deploy the bogie was reached relatively quickly. The aft bogie wheel drive actuator was the logical mechanism to pull the bogie into its final configuration. The aft bogie wheel drive, as designed for performing its primary rover traverse function, is able to supply up to 333 N (75 lbf) of deployment force. The addition of this capability brought with it both mass and complexity impacts to the design of the rover and the lander. On the rover, the bogie was split into two distinct structural elements, each having to house a portion of the mechanical components necessary to allow the bogie to deploy and latch into its final position. On the lander, a small, cogged platform was added to each of the aft wheel restraints, designed specifically to engage the wheel cleats and guarantee maximum traction during deployment.

The mechanism by which the aft bogie member moved within the forward bogie was originally slated to be skids to reduce system mass. The final design, however, was a system of roller assemblies supported by spring elements. The basis of this decision was the desire to decrease the friction in the design and increase the bogie's ability to tolerate thermal distortion. In addition, it was felt that rolling elements would be more tolerant to debris that could be ingested into the moving components during deployment. Whereas a sliding motion could seize due to a small amount of debris, a rolling system would be more forgiving, resulting in a robust overall design approach. The increase in bogie mass was considered acceptable in order to increase the deployment's reliability.

The design goal of the bogie roller assemblies was to suspend the aft bogie within the forward bogie. Four pairs of roller assemblies support the aft bogie and remove 5 of 6 degrees of freedom. By placing the two forward pairs as far away from the aft pair, roller loads are minimized and the roller size correspondingly reduced. This is particularly important in the bogie, which is located in an area of the rover where space was at a premium. The station distance between the pairs of roller assemblies is 10 cm (see Figure 9).

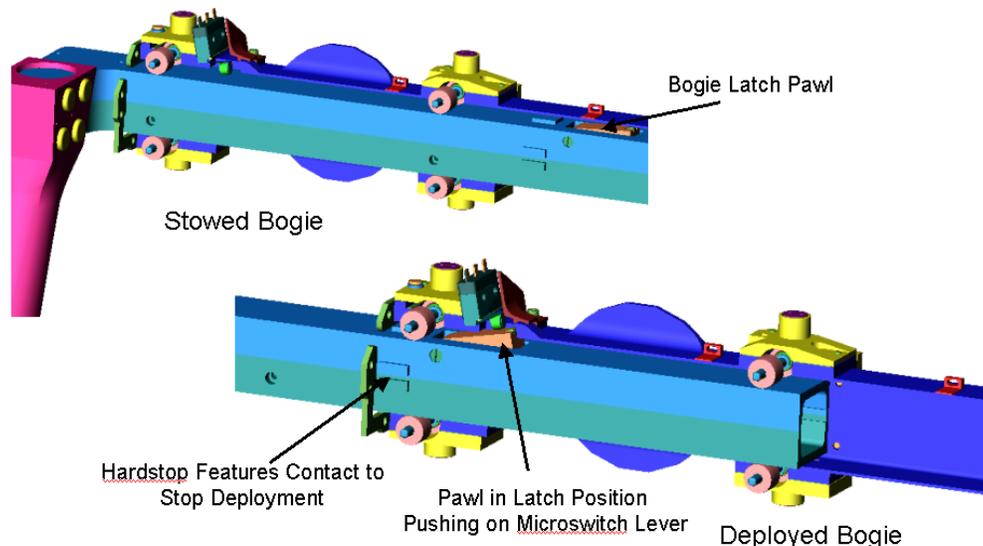


Figure 9. Bogie Deployment Diagram

A roller assembly consists of a roller pin with two needle bearings, one on each end of the pin. The rollers are positioned over the vertical portion of the aft bogie to allow load transfer through a stronger portion of the bogie cross-section. This roller placement also provides an efficient mechanical advantage for managing torsional loads applied to the aft bogie. Even with these considerations put into place, the wall thickness of the deployed aft bogie in the location where the roller rested had to be increased from 1 mm to 3 mm to withstand the roller point loads. The roller pin assemblies are nested between the aft bogie and a pair of belleville washers stacks. These stacks are needed to counteract any thermal or debris perturbations that could arise on the Martian surface during bogie deployment. A combination of washers in both parallel and series enabled the roller assembly to have a “soft” condition during the lightly loaded deployment phase and a “stiff” condition during the driving phase. The “soft” condition, engaged during deployment loading, was desired in order to reduce the drag in the roller needle bearings. Final analysis eventually required the addition of a stiffness phase to the roller design. Analysis of potential rover egress/driving “drop” cases indicated that the roller pins would fail in bending, despite being fabricated from MP35N high strength steel. Based on the results of this analysis, a decision was made to by-pass the belleville washer stacks during this large intermittent load and transmit it directly through the 440C steel roller sleeve and into the roller cover (see Figure 10).

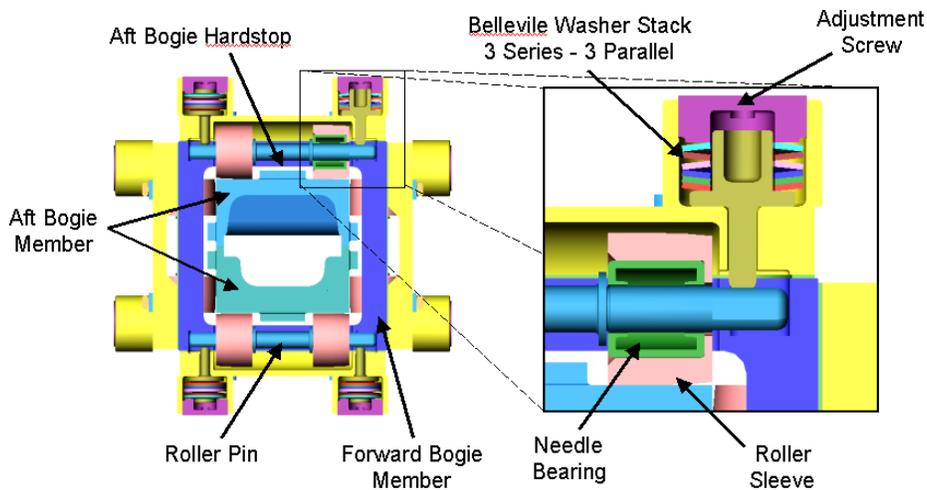


Figure 10. Cross-section of Bogie Roller Assemblies

The nominal applied load to the aft bogie wheel during bogie deployment is about 15% of the rover weight, or 97 N (22 lb) on Mars. This load increases as the rover is pitched up or sideways. A set of thermal tests were performed at room temperature and $-70\text{ }^{\circ}\text{C}$ to determine the assembly deployment margins. The tests showed a relatively small difference in the force required to deploy the bogie up to a 150% nominal applied load. Past this point the deployment force increases sharply. The worst-case deployment force of 224 N when a 222 N load was applied remained within acceptable limits of the wheel drive actuator’s 333 N capability (see Figure 11).

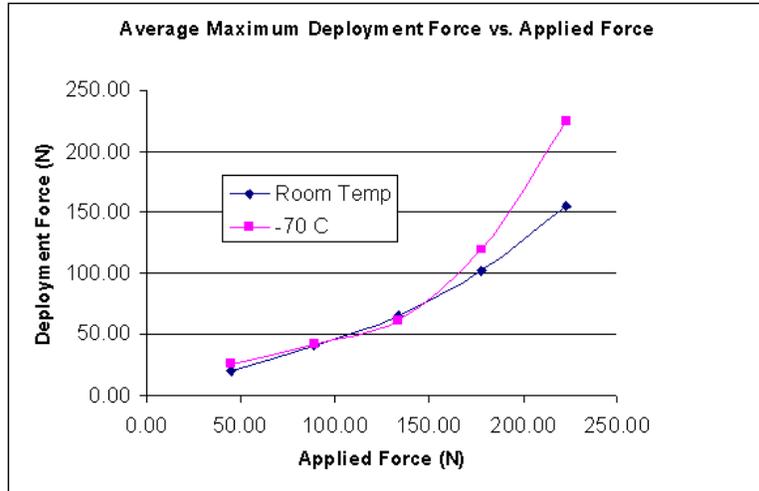


Figure 11. Results of Deploying Bogie at Cold Extreme

The bogie latch is a variation on the same basic latch design philosophy of the rocker-bridge latch: introduce an object that will not permit the further motion of the mechanism in any direction. Near the end of bogie deployment, an aft bogie-mounted latch pawl rotates upward into an opening in the forward bogie. A 12 degree deployment pawl angle was utilized to transfer the pawl load into the forward bogie with the addition of little mass.

Problems and Resolutions

Bogie Latch Pawl Design

During several of the most extreme rover mechanical validation and verification stand-up tests, the bogie pawl failed to fully rotate into its latched position. The failure was determined to be the result of the aft bogie rotating relative to the forward bogie along the deployment axis. The intentionally low stiffness designed into the bogie for reduced deployment loads was allowing the aft bogie to rotate up to 6 degrees under earth gravity, enough rotation to cause the latch pawl to hit the edge of the latch opening in the forward bogie, keeping it from fully latching.

A new bogie latch pawl was designed that had tapered edges that eliminated the previous interference. Fortunately, the original bogie pawl had sufficient margin to tolerate a reduction in cross-section (Figure 12).

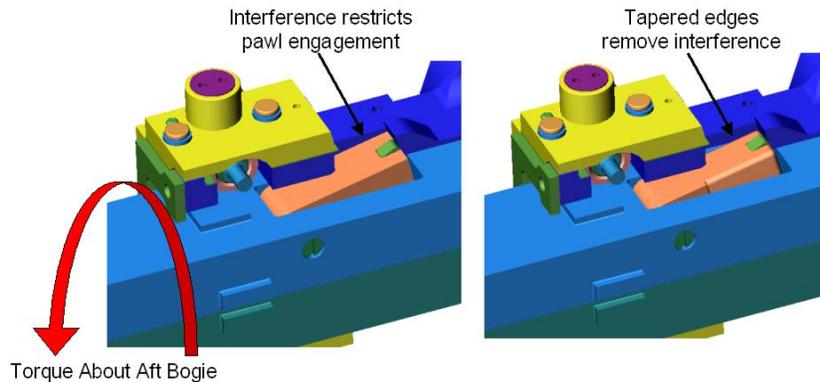


Figure 12. Original and Final Bogie Latch Pawl Design

Lesson Learned: Test the hardware under extreme conditions as soon as possible in the development phase. Testing will expose oversights in designs such as in this case where the non-linear stiffness of the mechanism was underestimated and resulted in a latch functional failure.

Implementation of Microswitches

The three primary components of the microswitch assemblies are the microswitch bracket, the microswitch, and the microswitch extension actuator (Figure 13). Each of the three unique latches utilize Honeywell 9HM30-REL-PGM microswitches to indicate if their respective latch had successfully engaged. The placement of the microswitches was such that the lever arm of the microswitch would be triggered by the latch pawl pushing on the arm. Due to limited space and the fear that the microswitch lever arm might be overextended, microswitch actuators Honeywell JS-151 and JS-152 were used to extend the range of the microswitches.

The features by which each microswitch was attached to its respective joint were intentional designed with large clearance holes. The thought behind this highly adjustable interface was to ensure that the microswitch could easily be positioned to register if a successful latch action had been achieved. However, this type of interface meant there was significant variability between the rovers in microswitch actuation. In addition, the interface left the microswitch susceptible to small changes in position due to dynamic loading or thermal gradients.

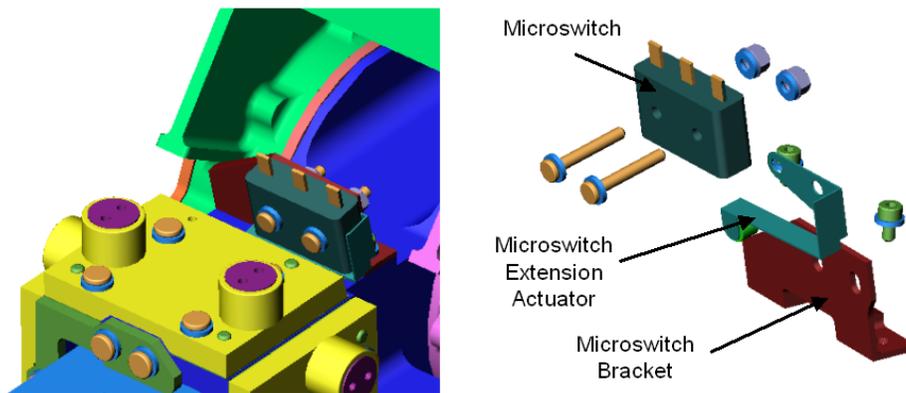


Figure 13. Bogie Microswitch Assembly

Testing of the rover standup phase yielded inconsistent results from the deployment microswitches. As a result, a detailed adjustment protocol was established for each of the microswitch assemblies that yielded consistent results. A new latch verification sequence was developed as an added measure to increase the understanding of the mobility latch states for use during rover standup and deployment. A post-latching command was added to each of the deployment sequences that drove the joint in the stow direction. The resulting stall of this motion was clear indication that a joint had successfully latched.

Lesson Learned: The use of microswitches to verify a latched condition should not be entered into lightly. The proper implementation of microswitches requires a consistent method by which the microswitch is positioned with respect to the relevant components. An alternate method such as driving the joint in the opposite direction and monitoring current can produce telemetry that is less dependent on the fine adjustments associated with microswitches.